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# On the need of distinguishing ductile and brittle failure modes in timber connections with dowel-type fasteners

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ABSTRACT

Timber connections can fail in a ductile or in a brittle way. A structural design that guarantees a ductile behaviour in case of failure is desirable, especially when facing extreme situations such as earthquakes. This work discusses how the European Yield Model (based on a ductile failure mechanism), included in many standards, combined with a reduction of the effective number of fasteners may provide too conservative results, which may inadvertently lead to risky situations in which a connection assumed to fail under a ductile mechanism would actually fail in a brittle manner. Within this paper, a proposal to improve the discrimination ability to correctly predict the failure mode is proposed.

## 1. Introduction

Timber construction is steadily growing, as an answer to an increasing demand for sustainability in the building sector. An adequate design of the structure is therefore needed to ensure the safety and to optimise the material resources. Connections play an utmost role in timber engineering. Several studies [1,2] pointed out that 25% of recent collapses from timber structures were related to failure of connections.

Timber connections may fail in a ductile or a brittle way, as qualitatively shown in Fig. 1. Since timber breaks in a brittle manner under bending and tension, the ductility of timber structures is usually provided by connections. Therefore, high ductility values in connections are desirable, especially in seismic regions [3]. On one hand, the sequential deformation of a ductile failure (Fig. 1a) allows to identify a possible failure in time to prevent it and contributes to a proper robustness of the structure [4]. On the other hand, a brittle failure (Fig. 1b) implies a sudden collapse of the structure that may lead to human or material damage. Despite their relative importance, brittle failure modes are still quite unknown, as demonstrated by a survey performed by Working Group 3 of the Cost Action FP1402 [5], in which 30% of the respondents (mainly practitioners) were not aware of it.

The ductile design of connections has been traditionally based on the European Yield Model EYM, which assumes the plastic embedment failure of the wood and the yielding of the fastener (Fig. 2a). This model is included in many structural standards, as it is the case of Eurocode 5 [6] or the New Zealand Standard draft [7].

The models dealing with brittle failure are more recent. Early attempts date to the 1980's [8]. Since then, several authors have proposed different models for brittle failure modes. Their inclusion in standards such as Eurocode 5 [6] (as an informative annex), CSA Standard O86-09 [9] or the draft of the New Zealand standard [7] is quite recent and still on going. An overview and comparison of the most representative models was provided by Cabrero and Yurrita [10].

In the case of Eurocode 5 [6], the EYM is combined with the reduction parameter $n_{ef}$ [11], which multiplies the capacity of a single fastener (obtained by the EYM) by the effective number of fasteners $n_{ef}$, usually lower than the actual one. This factor, together with the requirements of minimum spacings between fasteners, intends to prevent several brittle failure modes such as splitting (Fig. 2b) or row shear (Fig. 2c). Block shear (Fig. 2d) was not considered in the prenormative version of the Eurocode 5 [12]. It was, however, included in the final version as an informative (not compulsory) Annex A.

Several test campaigns, considering both connections with large diameter fasteners i.e. dowels and bolts [13] and small diameter fasteners i.e., nails, screws, and rivets [14], demonstrated that brittle failure modes can be observed even when the prescribed minimum spacings are met. In the case of large diameter fasteners (those that usually fully penetrate the timber member, such as dowels and bolts), Yurrita and Cabrero [15] used the experimental results from an comprehensive database to develop a new model dealing with all possible brittle failure modes of connections loaded parallel-to-grain, depicted in Fig. 2, which improved the prediction accuracy of the existing models [6,7,16,17].

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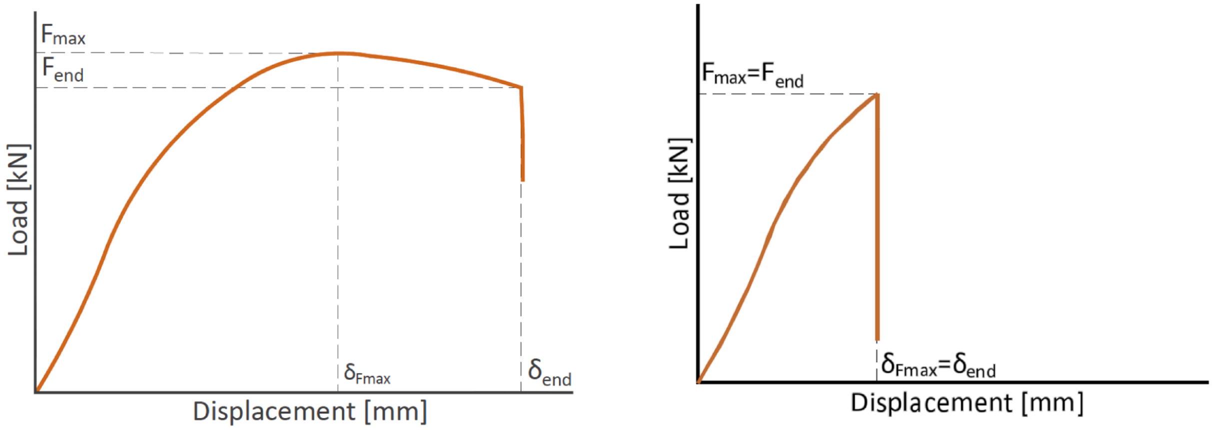



(a) Ductile behaviour (b) Brittle behaviour

**Fig. 1.** Load-slip curves of the possible behaviours of a timber connection.

Moreover, as the $n_{ef}$ takes account of brittle failure modes within a ductile based model, it does not properly inform the designer on the actual expected failure mode of the connection. The use of brittle failure models allows to separate the calculation of ductile and brittle failure modes, so the designer is able to determine the expected failure mode. However, for that purpose, the prediction accuracy of both ductile and brittle models must be accurate enough to avoid false predictions.

The conservative trend resulting from the combination of the EYM with the reduction factor $n_{ef}$, may imply unwanted situations in which a brittle failure mode may govern the connection behaviour, although a ductile failure mode was predicted (as the ductile capacity was lower). This paper discusses the possible existence of such situations and quantifies them.

The paper is structured as follows: Section 2 includes a brief description of the analysed type of structural connections, their brittle failure modes, and existing models. Section 3 analyse a database of ductile tests and demonstrates the conservative trend of Eurocode 5 [6]. Section 4 presents an exhaustive parametric analysis that compares Eurocode 5 [6] ductile model with the brittle model from Yurrita and Cabrero [15] and identifies those cases where a brittle failure mode is achieved even if a ductile one is expected. Finally, in Section 5, an increase of the load-carrying capacity predicted by Eurocode 5 [6] is suggested to minimise the risks of reaching an unexpected brittle failure mode.

## 2. State of the art

### 2.1. Failure modes of timber connections

As stated before, timber connections with dowel-type fasteners loaded parallel-to-grain may reach a brittle or ductile failure mode. The resulting failure mode depends on the material and geometrical properties of the connection.

A ductile failure mode implies that the yielding of the fastener occurs before cracking of the wood, while in a brittle failure mode, the failure of the wood happens before the plastic response of the fasteners is reached. Typical brittle failure modes are shown in Fig. 2. Of course, the material properties of the structural elements play an active role on the governing failure mode. But apart from them, geometrical parameters of the connection may also become relevant, as the spacings between fasteners (large spacings increase the chances of a ductile failure mode), the fastener slenderness (a stocky fastener requires a higher applied load to yield and develop a ductile mechanism), or the joint configuration.

Fig. 3 depicts typical configurations of timber-to-steel connections (similar cases exist for timber-to-timber connections by replacing the steel plate by another timber element). The number of shear planes $n_s$ (one -Fig. 3a-, a-, two -Fig. 3b and Fig. 3c- or multiple shear planes -Fig. 3d-), or the position of the timber element, as an outer element (Fig. 3a, Fig. 3b or the outer elements from Fig. 3d) or an inner element (Fig. 3c and the inner element from Fig. 3d) also affect to the resulting yielding behaviour of the fastener.

#### 2.1.1. Ductile failure mode of connections

Ductile failure mode is due to the combination of the embedment of the wood and the yielding of the fastener.

Different yielding modes may be produced depending on the material and geometrical properties of the connections. The embedment strength depends on both the timber density $\rho$ and the fastener diameter $d$, while the yielding of the fastener is related to its yielding moment $M_y$, defined by the steel yield strength $f_y$ and the fastener diameter $d$. Those factors, in combination with the thickness of the timber elements and steel plates and the joint configuration, determine the number of plastic hinges per shear plane in the connection, as depicted in Fig. 4.

Several authors [18,19] have developed analogue formulae for multiple shear planes connections, which are not explicitly included within Eurocode 5 [6].

The EYM load-carrying capacity of fasteners submitted to large deformations (plastic hinges) may be increased by additionally considering the rope effect, which is produced by the axial capacity of fasteners submitted to lateral loads. This extra contribution is limited to 25% and 0% of the calculated load-carrying capacity for bolts and dowels, respectively.

#### 2.1.2. Brittle failure mode of connections

Brittle failure mode is due to a crack of the wood usually taking place before the steel fasteners reach their plastic range, leading to a sudden collapse of the connection. The most common brittle failure modes of connections with large diameter fasteners loaded parallel-to-grain (Fig. 2) are:

- Splitting (Fig. 2b): it is formed by a longitudinal crack along the row of fasteners due to tensile stresses perpendicular-to-grain. This

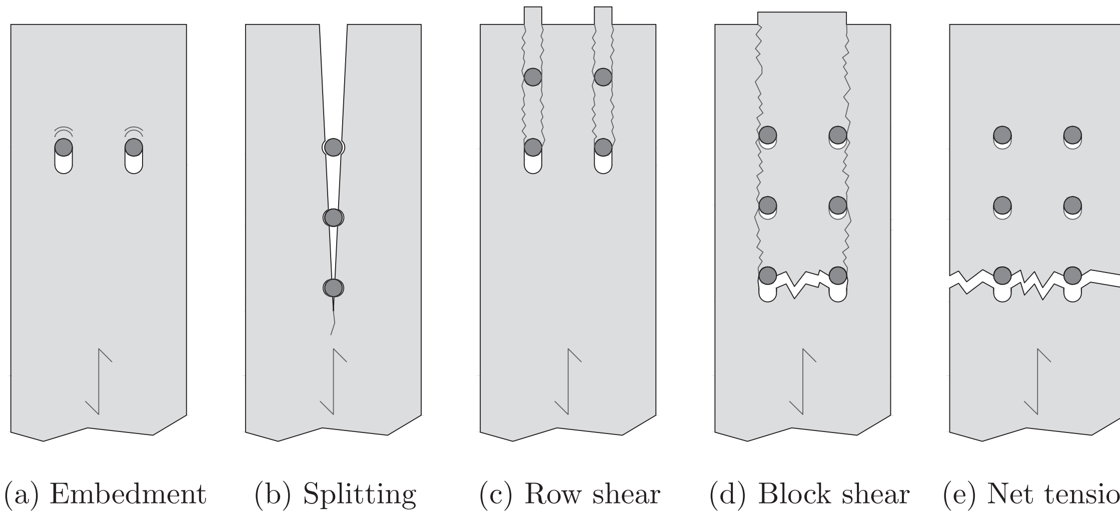



**Fig. 2.** Possible failure modes of a timber connection with dowel-type fasteners: embedment (right hand-side, a) is the only ductile failure mode, the rest are brittle.

failure mode affects locally in a single row of fasteners and, therefore, it may not be the cause of the final global failure of a connection with multiple rows.

- Row shear (Fig. 2c): shear stresses generate two parallel cracks along each row of fasteners of the connection.
- Block shear (Fig. 2d): it is generated by the tear out of the loaded timber area, defined by the connection perimeter. Two lateral shear cracks along the exterior rows of fasteners and a head tensile crack along the first column of fasteners are combined in this case.
- Net tension (Fig. 2e): it is defined by a crack generated on the net cross-sectional area at the beginning of the connection.

There are different proposals dealing with brittle failure modes.

Eurocode 5 [6] only considers block shear in its informative Annex A directly. As already stated, row shear and splitting are implicitly considered by combining the EYM with the reduction factor $n_{ef}$ and by respecting some spacing limitations.

The parameter $n_{ef}$ reduces the number of effective fasteners per row of fasteners. This factor is derived from the work by Jorissen [11]. It is used both to reduce the design capacity of the connection to prevent from some brittle failure modes such as row shear and splitting and, at the same time, to consider the uneven distribution of the load between fasteners. This uneven distribution is redistributed when the fasteners yield, since they cannot be loaded above their plastic capacity [20]. For large diameter fasteners such as dowels and bolts, $n_{ef}$ is defined as:

$$n_{ef} = \min \begin{cases} n_r \\ n_r^{0.9}\sqrt[4]{\dfrac{a_1}{13d}} \end{cases} \tag{1}$$

where $n_r$ is the number of rows of fasteners, $a_1$ is the spacing between rows and $d$ is the fastener diameter.

The New Zealand standard draft [7], which can be considered as an evolution of the model included in the Canadian standard CSA Standard O86-09 [9], is based on the model developed by Quenneville and Mohammad [21] and Mohammad and Quenneville [22]. It considers all the described failure modes (except splitting, as it is assumed that it cannot lead to the entire failure of a connection with two or more rows of fasteners) in separate calculations.

The proposal from Hanhijärvi and Kevarinmäki [16,17] considers all the described failure modes (both brittle and ductile) and are all studied together in a same calculation process. They also consider the possible interaction between stresses related to different failure modes.

The model proposed by Yurrita and Cabrero [15] also considers all failure modes separately, except splitting (which was additionally studied by Yurrita and Cabrero [23]). The effective thickness, defined by Yurrita and Cabrero [13], was used both for the models for large diameter fasteners [15,23,24] and small diameter fasteners [14,25]. An additional modification for brittle failure mode in connections with multiple shear planes was proposed by Yurrita et al. [24].

In the present work, the model of Yurrita and Cabrero [15] has been taken as the reference brittle model, since it was demonstrated to provide the most accurate results. For a further insight about the model and its accuracy, the reader is referred to Yurrita and Cabrero [15].

The model considers the failure modes depicted in Fig. 5 by defining the load carrying capacities of the involved failure planes (lateral shear planes L for row shear -Fig. 5a-; head tensile plane *H* for net tension -Fig. 5c and both planes for block shear -Fig. 5b).

## 3. Analysis of the prediction accuracy of Eurocode 5 for ductile failure mode

### 3.1. Database

A database of experimental tests has been used to evaluate the prediction accuracy of the model included in Eurocode 5 [6]. As shown in Table 1, the tests from a total of 7 experimental studies (Ehlbeck and Werner [26], Ehlbeck and Werner [27], Jorissen [11], Blaß and Schmid [28], Sandhaas [29], Hüner [30] and Misconel et al. [31]) were considered.

The compiled database focuses on the ductile tests (although some researchers reported also some splitting cases), gathering a total of 221 configurations (1518 single tests). It comprises both timber-to-steel (wood-steel-wood, *wsw*) and timber-to-timber (wood-wood-wood, *www*). Dowels were used as fasteners in 69.2% of the configurations, whereas bolts in the rest. Solid wood is the main timber product (65.2%), followed by glulam (25.8%) and LVL (9.0%). Regarding the type of wood, both softwood and hardwood are similarly represented (42.5% and 57.5%, respectively). Finally, almost half of the reported tests (47.5%) included two or more rows of fasteners, whereas the rest of

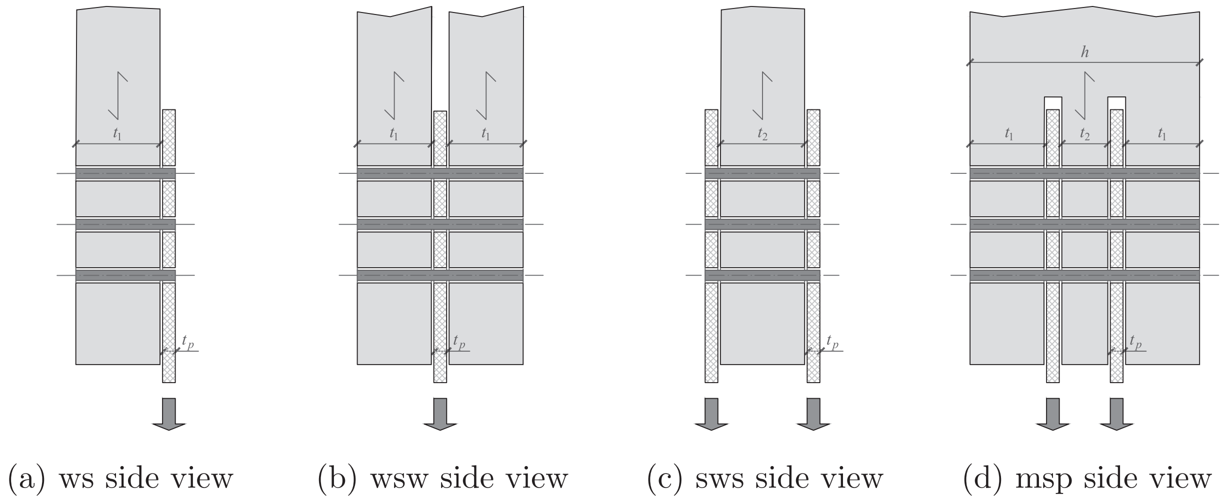



**Fig. 3.** Possible configurations of a timber connection combined with steel plates.

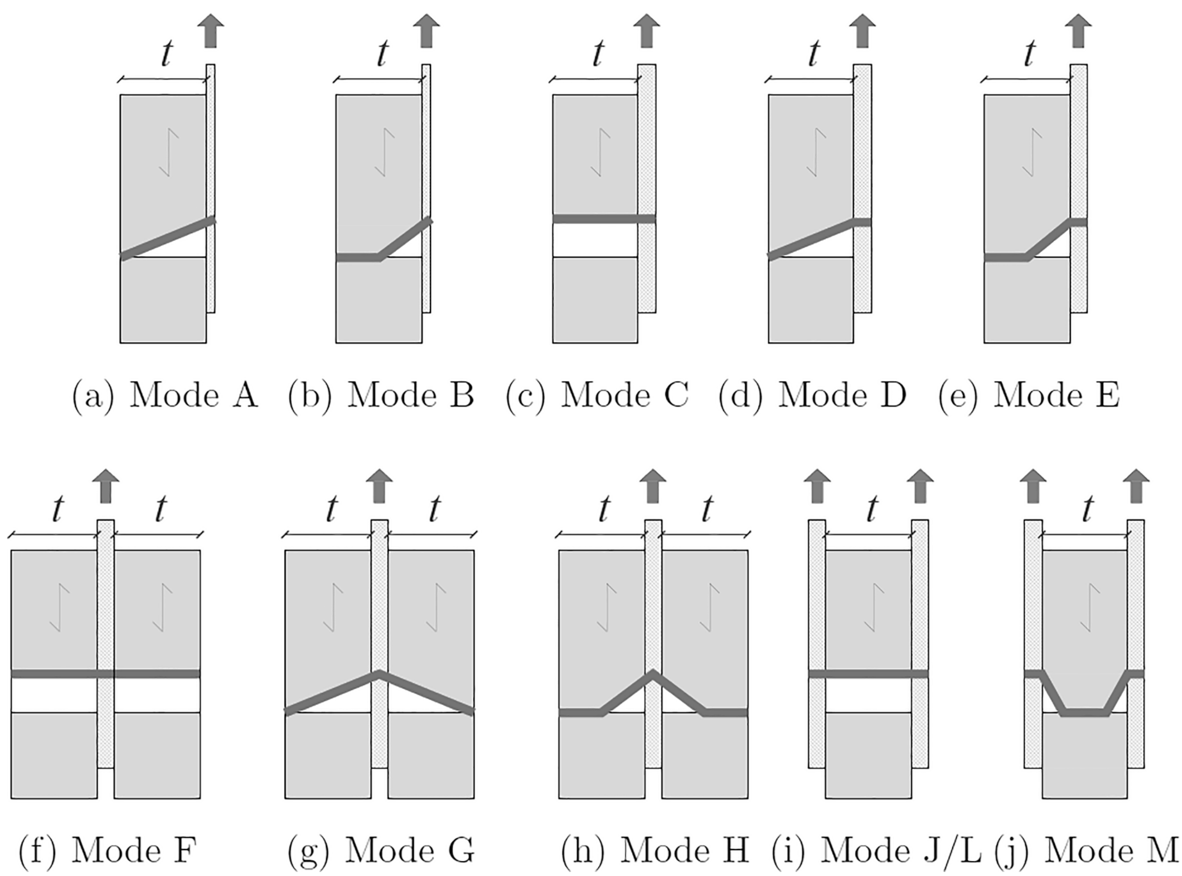


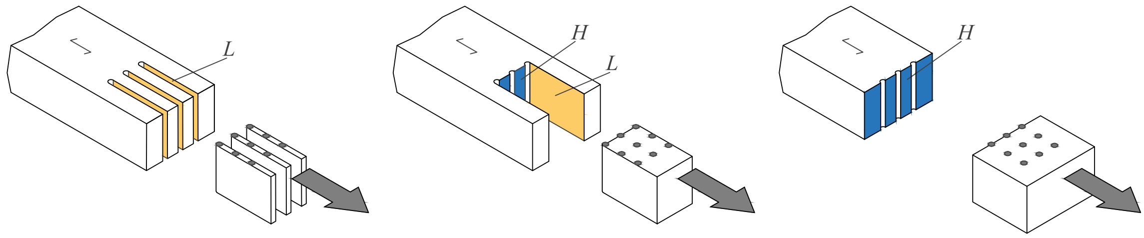

**Fig. 4.** Yielding modes of the fastener considered by the EYM for timber-to-steel connections. Similar cases are considered for timber-to-timber connections.

the configurations included only one row of fasteners. Table 1 provides further information about each of the studied works.

### *3.2. Comparison between the test results and the predictions obtained from Eurocode 5*

As a first step, the test results have been compared with the load-carrying capacity predicted by the approach described in Eurocode 5 [6], that is, the combination of the EYM with the number of effective fasteners $n_{ef}$ and the rope effect (considered as 0% for dowels and 25% for bolts).

The small number of replicates for each configuration in the existing campaigns does not allow to obtain an accurate characteristic load-carrying capacity and, hence, the validation is performed at the mean level. The required mean properties are obtained from the characteristic values following the procedure explained by Jockwer et al. [32] and Cabrero et al. [33] which is based on the probabilistic model for timber proposed by the Joint Committee on Structural Safety [34], previously




(a) Row shear (b) Block shear (c) Net tension

**Fig. 5.** Loading planes (lateral shear L, and head tensile H) related to each failure mode.

**Table 1**
Summary of the tests used for the validation of ductile failure.

| Author | Number of | | Joint scheme | | Fastener Type | | Timber product | | | Timber class | | Nº columns | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Config. | Tests | *wsw* | *www* | Bolt | Dowel | Glulam | LVL | Solid | Softwood | Hardwood | 1 | ⩾2 |
| Ehlbeck and Werner [26] | 45 | 135 | - | 45 | - | 45 | 45 | - | - | - | 45 | - | 45 |
| Ehlbeck and Werner [27] | 47 | 141 | - | 47 | 7 | 40 | - | - | 47 | - | 47 | - | 47 |
| Jorissen [11] | 59 | 924 | - | 59 | 59 | - | - | - | 59 | 59 | - | 51 | 8 |
| Blaß and Schmid [28] | 23 | 83 | 23 | - | - | 23 | - | - | 23 | 23 | - | 23 | - |
| Sandhaas [29] | 36 | 180 | 36 | - | - | 36 | 12 | 12 | 12 | 12 | 24 | 36 | - |
| Hübner [30] | 3 | 15 | 3 | - | - | 3 | - | - | 3 | - | 3 | - | 3 |
| Misconel et al. [31] | 8 | 40 | 8 | - | 2 | 6 | - | 8 | - | - | 8 | 6 | 2 |
| Total Number | 221 | 1518 | 70 | 151 | 68 | 153 | 17 | 20 | 144 | 94 | 127 | 116 | 105 |
| % | - | - | 31.7% | 68.3% | 30.8% | 69.2% | 25.8% | 9.0% | 65.2% | 42.5% | 57.5% | 52.5% | 47.5% |

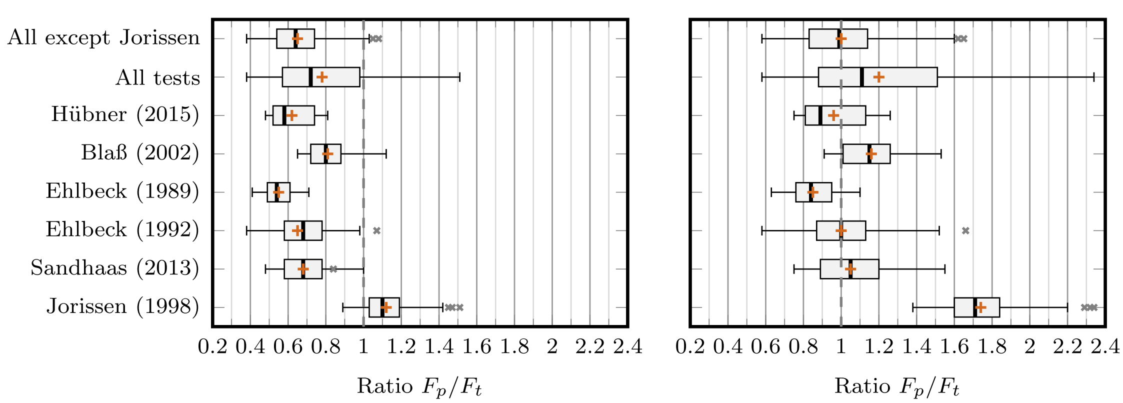
used in other works [10,13–15,23–25,35].

The boxplot graphic in Fig. 6 separately analyses the prediction accuracy obtained by Eurocode 5 [6] when compared with the tests of each of the test campaigns (due to the small amount of tests from Hübner [30], it has been considered together with those from Misconel et al. [31]). The ratio between the predicted load capacity $F_p$ and the tested load capacity $F_t$ is used as the comparison parameter, and the ideal ratio $F_p/F_t = 1$ is given by a vertical dashed line.

The results show a consistent conservative trend on the prediction of the load-carrying capacity. Average and median values from the analysis of the tests performed by Ehlbeck and Werner [26], Ehlbeck and Werner [27], Sandhaas [29], Hübner [30] and Misconel et al. [31] are between 0.53 and 0.67. Slightly less conservative values (around 0.80) are obtained in the case of Blaß and Schmid [28].

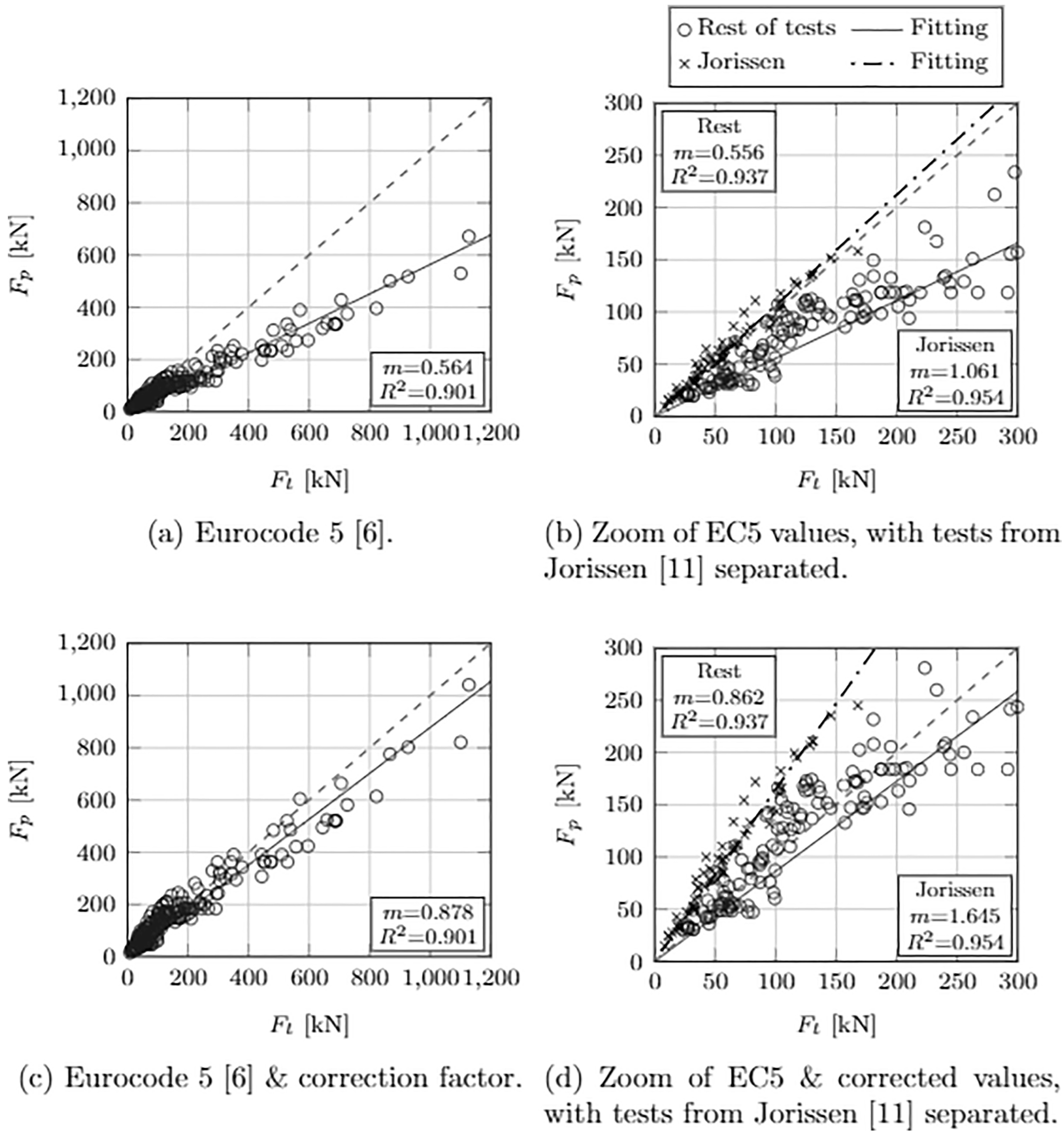
The only case with a different trend is Jorissen [11], where average and mean values close to 1 (around 1.05) are obtained. The joint configuration, timber product, type and size of fasteners used, or the number of rows have been considered as possible reasons. However, no clear explanation for this dissimilar trend has been found. In the boxplots in Fig. 6, two different series considering all the test together, and without the ones from Jorissen [11] are given.

Fig. 7a studies the tests altogether, plotting the load-carrying capacity from tests in the abscissa axis, and the predicted values in the ordinates axis. A dashed line depicts the ideal slope $m = 1$. The obtained slope $m = 0.564$ of the fitting line confirms the conservative trend of Eurocode 5 [6]. However, the high coefficient of correlation $R^2 = 0.917$, demonstrates that, despite this conservative trend, the model is quite consistent. Fig. 7b is a zoom of the former graphic, taking into account the range of tests with a load-carrying capacity within a range between 0 and 300 kN. The tests from Jorissen [11] are plotted differently, so




(a) Eurocode 5 [6] (b) Eurocode 5 [6] & correction factor of 1.55

**Fig. 6.** Boxplot assessing the accuracy obtained by the Eurocode 5 [6] when compared with the test results from the studied authors, considering the accuracy of the ratio between the predicted failure load $F_p$ and the tested failure load $F_t$.




(a) Eurocode 5 [6].

(b) Zoom of EC5 values, with tests from Jorissen [11] separated.

(c) Eurocode 5 [6] & correction factor.

(d) Zoom of EC5 & corrected values, with tests from Jorissen [11] separated.

**Fig. 7.** Comparison between the load capacity values obtained from the tests $F_t$ and the corresponding theoretical values $F_p$ predicted by the ductile approach from the Eurocode 5 [6], and when applying the correction factor of 1.55.

they can be distinguished.

Fig. 6b shows a corrected boxplot in which a factor of 1.55 has been applied to the previous values from Eurocode 5 [6] to obtain an ideal average ratio $F_p/F_t = 1$ for all tests (except the ones from Jorissen [11]), and an improved mean prediction ability.

Fig. 7c and Fig. 7d show how the former results (Fig. 7a and Fig. 7b) are modified when the correction factor of 1.55 is applied. The resulting slope $m$ improves to a value of 0.88 (reduced to 0.86 when the tests from Jorissen [11] are considered separately in Fig. 7d).

## 4. Parametric analysis to evaluate the discrimination ability between ductile and brittle failure modes

As shown above, the results from Eurocode 5 [6] are conservative. Although this trend could be considered in the side of safety, it may however lead to risky situations, in which a connection designed to fail in a ductile manner would prematurely reach a brittle failure mode instead, as the predicted ductile load-carrying capacity could be higher than the actual ductile capacity.

Moreover, Eurocode 5 [6] combines the EYM with the number of effective fasteners $n_{ef}$, and hence considers simultaneously ductile and

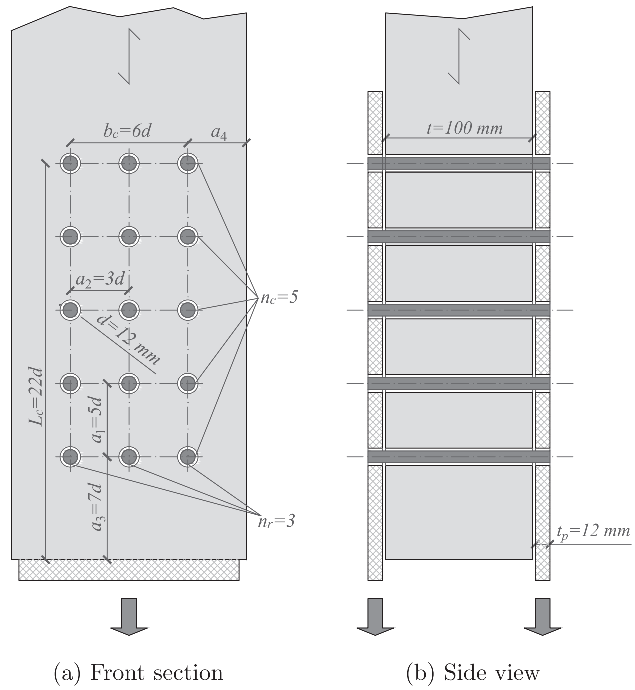



**Fig. 8.** Geometry of the connection used for the parametric analysis.

some cases of brittle failure mode, like splitting or row shear. Other brittle failure modes such as block shear are not included. As a consequence, this model not only obtains too conservative results, it does not include all brittle failure modes; and it additionally hinders the possibility to determine whether a connection will fail in a brittle or in a ductile way.

A parametric study has been conducted to study the effect of the observed conservative trend when determining the failure mode. The approach from Eurocode 5 [6] with its corrected version after applying the factor of 1.55 derived from the analysis in Section 3, in combination with the brittle failure model proposed by Yurrita and Cabrero [15] are also analysed.

### 4.1. *Analysis of one connection*

#### 4.1.1. *Geometry and materials of the connection*

Before presenting the overall results of the conducted analysis, an example of one of the studied connections is herein presented in Fig. 8. The considered case is a steel-wood-steel *sws* connection with a timber thickness $t = 100$ mm, fasteners of diameter $d = 12$ mm and steel plates of $t_p = 12$ mm (considered as thick plates according to Eurocode 5 [6]). The connection includes a total of 12 fasteners distributed in a 3x5 mesh (number of rows $n_r = 3$ and number of columns $n_c = 5$). The basic spacing distances ($a_1, a_2, a_3$ and $a_4$ are taken always as the minimum prescribed in Eurocode 5 [6] to guarantee a ductile failure mode (smaller spacings are assumed to increase the risk of a brittle response).

Two different steel grades (6.8 and 12.9) for the fasteners and two timber products (C24 [36] and beech LVL80S [37]) were used.

#### 4.1.2. *Parametric analysis of the connection example*

The parametric analysis studies the impact of varying several parameters on connections as the one depicted in Fig. 8 which has been used as the basis geometry.

The studied parameters are: timber member thickness $t$ (Fig. 9), fastener diameter $d$ (Fig. 10), spacing between columns of fasteners $a_1$ (Fig. 11), spacing between rows of fasteners $a_2$ (Fig. 12) and distance to the loaded edge $a_3$ (Fig. 13). The distance $a_4$ has not been considered as its influence will affect mainly to net tension failure, which is calculated exactly in the same way in Eurocode 5 [6] and in the brittle model from Yurrita and Cabrero [15].

For each case, results from the four possible combinations between the two fastener steel grades and timber products are provided. The combination of timber *C*24 with the steel grade 6.8 (Fig. 9a, Fig. 10a, Fig. 11a, Fig. 12a, Fig. 13a) is a good example of a low profile connection. Just in the opposite side, a high strength connection is obtained by combining beech LVL80S and steel grade 12.9 (Fig. 9d, Fig. 10d, Fig. 11d, Fig. 12d, Fig. 13d). In between, a case of softwood with high steel grade -*C*24 + steel 12.9- (Fig. 9b, Fig. 10b, Fig. 11b, Fig. 12b, Fig. 13 and a hardwood with a mild steel grade -beech LVL80S + steel 6.8- (Fig. 9d, Fig. 10d, Fig. 11d, Fig. 12d, Fig. 13d) are also considered. Since the former analysis of the tests considered the mean level of the material properties, the same values are applied in the parametric analysis.

In every graph, the variation of the studied parameter is shown in the abscissa axis. In the case of distances between fasteners ($a_1, a_2$ and $a_3$) the ratio between the parameter and the fastener diameter $d$ is plotted instead of the absolute distance. The predicted load $F_p$ is plotted in the ordinate axis. The values from three models are plotted: the brittle model from Yurrita and Cabrero [15], the ductile approach from Eurocode 5 [6], and the corrected version of the former one by applying the coefficient of 1.55 obtained in Section 3. Vertical dashed lines are used to limit the intersection points between the brittle behaviour according to Yurrita and Cabrero [15] and Eurocode 5 [6] with the correction factor. Additionally a vertical continuous line is plotted as a reference of the spacing limits $a_1 = 5d$, $a_2 = 3d$ and $a_3 = 7d$ provided by Eurocode 5 [6].

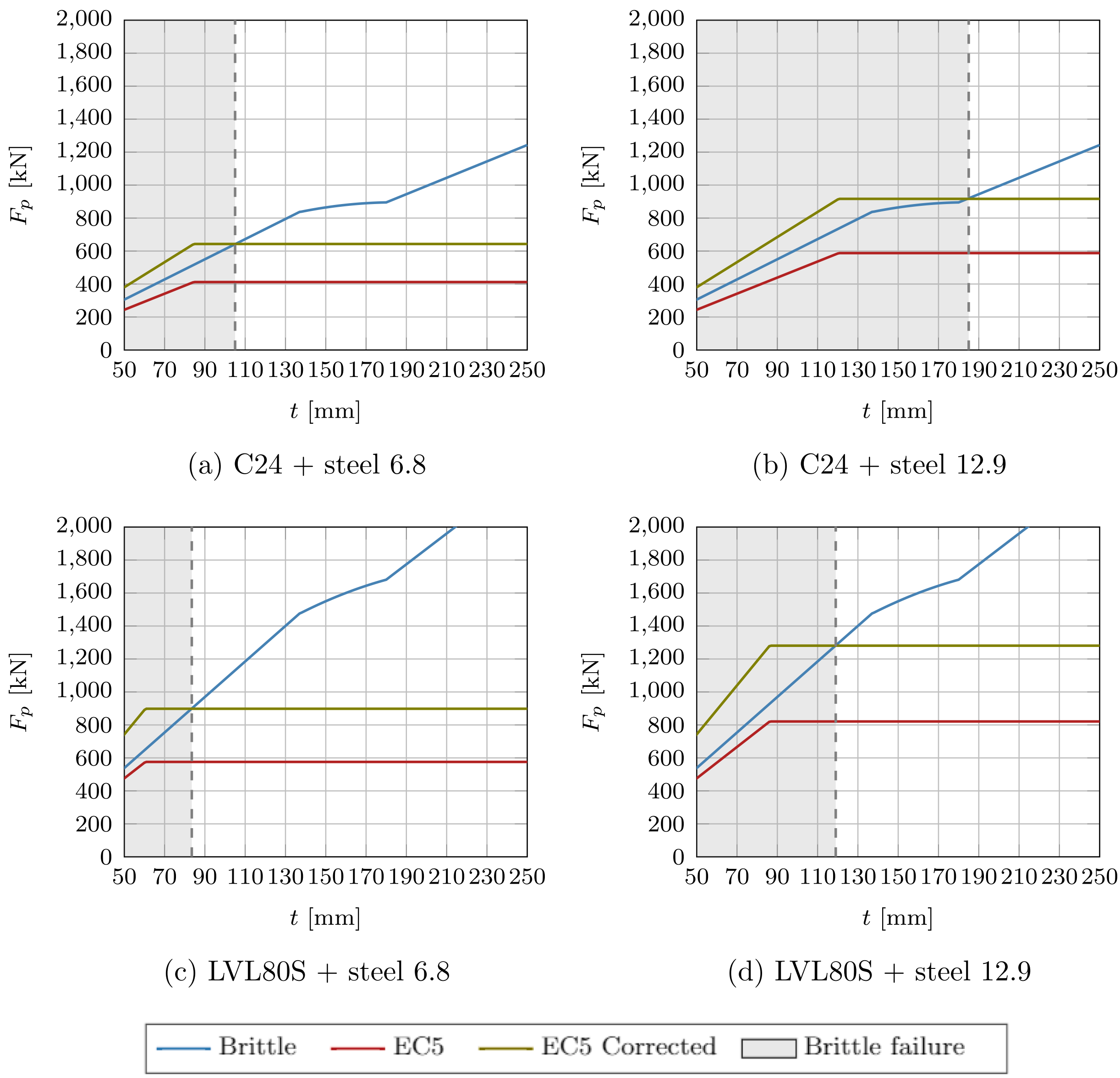



**Fig. 9.** Parametric analysis of the influence of the timber thickness $t$ on the predicted load capacity $F_p$ considering the brittle model from Yurrita and Cabrero [15], the model from Eurocode 5 [6] and its corrected version according to Section 3.

The gray-filled areas of the graphs correspond to those where the brittle model [15] reaches a lower load-carrying capacity than the corrected load capacity of Eurocode 5 [6], assumed as an accurate model for ductile failure mode. The values from the models from Eurocode 5 [6] include the number of effective fasteners and, therefore, do not discriminate between ductile and brittle failure modes. The configurations in which brittle failure mode may govern, without the designer being aware, are represented by these shaded parts of the graphs.

It may be observed how the current model in Eurocode 5 [6], including the $n_{ef}$ parameter, consistently obtains lower load-carrying capacities than the brittle model. As a result, the previously discussed conservative trend of Eurocode 5 [6] assumes a ductile prediction even when brittle failure mode may occur.

Analysis of the influence of the thickness of the timber member *t*.

The influence of the thickness of the timber member is shown in Fig. 9. A range within 50 and 250 mm has been considered in the analysis, as the most representative of the thicknesses applied in timber engineering.

In general, all cases with low timber thickness are expected to reach brittle failure mode. The limit thickness values depend mostly on the steel grade of the fastener. When the lower steel grade 4.8 is considered, the limit stays in between 104 mm for C24 timber (Fig. 9 and 83 mm for LVL80S (Fig. 9c). When the steel grade 12.9 is used, the thickness limit is increased up to 186 mm for C24 (Fig. 9 and 118 mm for beech LVL80S (Fig. 9d) In those timber thickness in which ductile failure mode is guaranteed, the yielding mode of the fastener corresponds to two hinges.

Analysis of the influence of the fastener diameter *d*.

The analysis of the impact of the fastener diameter $d$ is given in Fig. 10. The range of the studied diameters matches with the existing diameters of dowels (between 6 and 30 mm).

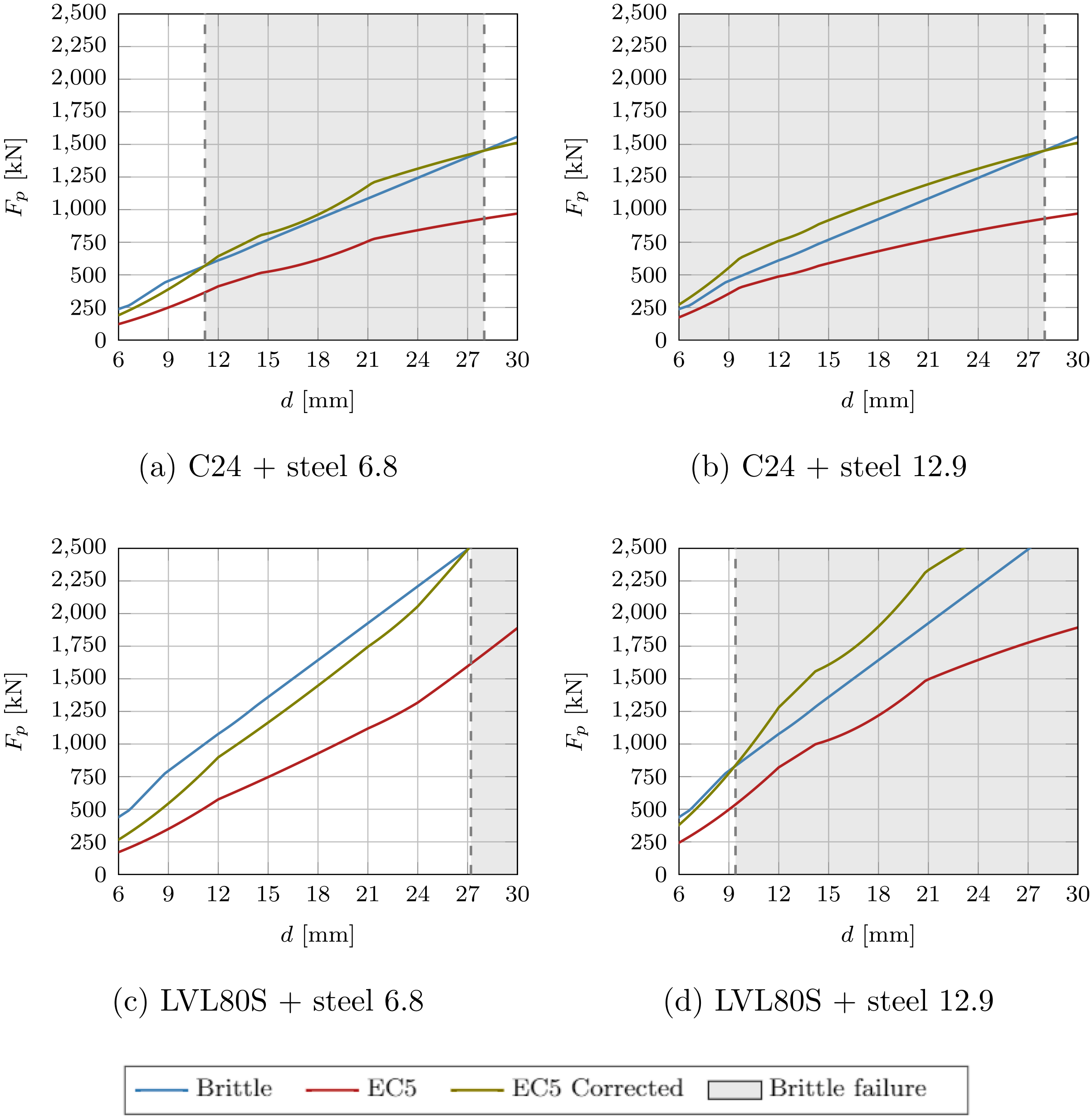



**Fig. 10.** Parametric analysis of the influence of the fastener diameter $d$ on the predicted load capacity $F_p$ considering the brittle model from Yurrita and Cabrero [15], the model from Eurocode 5 [6] and its corrected version according to Section 3.

As shown, unexpected brittle failure modes (gray-shaded areas, those where the current Eurocode 5 [6] model conservatively predicts a ductile capacity where brittle failure mode may govern) may happen in the whole analysed range, as brittle failure modes may happen for both small and large diameters. Again, the cases with the high steel grade 12.9 are riskier, with almost the whole part of the graphs shaded in gray (Fig. 10b and Fig. 10d). The opposite trend is found when the steel grade 6.8 is combined with LVL80S (Fig. 10c).

Analysis of the influence of the spacing between columns of fasteners $a_1$.

The impact of the variation in the spacing between columns of fasteners is given in Fig. 11. The variation plotted in the graphs is from $a_1/d = 1$ to $a_1/d = 10$, although for the main analysis only the range $a_1/d = 5$ to $a_1/d = 10$ is considered. The limit $a_1/d = 5$ established by Eurocode 5 [6] is given by a vertical black line.

A similar trend as above may be observed: almost no problems respecting the limitation of $a_1/d = 5$ are observed in the material combinations with steel 6.8 (Fig. 11c and Fig. 11a, although in this latter case a distance of $a_1/d = 6.2$ would be required to obtain ductile failure mode). In contrast, a much higher spacing distance $a_1$ is required to achieve a ductile behaviour for the cases with steel grade 12.9 (Fig. 11d and Fig. 11b).

Analysis of the influence of the spacing between rows of fasteners $a_2$.

The study of the spacing between rows of fasteners $a_2$ is given in Fig. 12. The same range of values as in the case of $a_1$ is used, although this time, the limit established by Eurocode 5 [6] for dowels is $a_1/d = 3$.

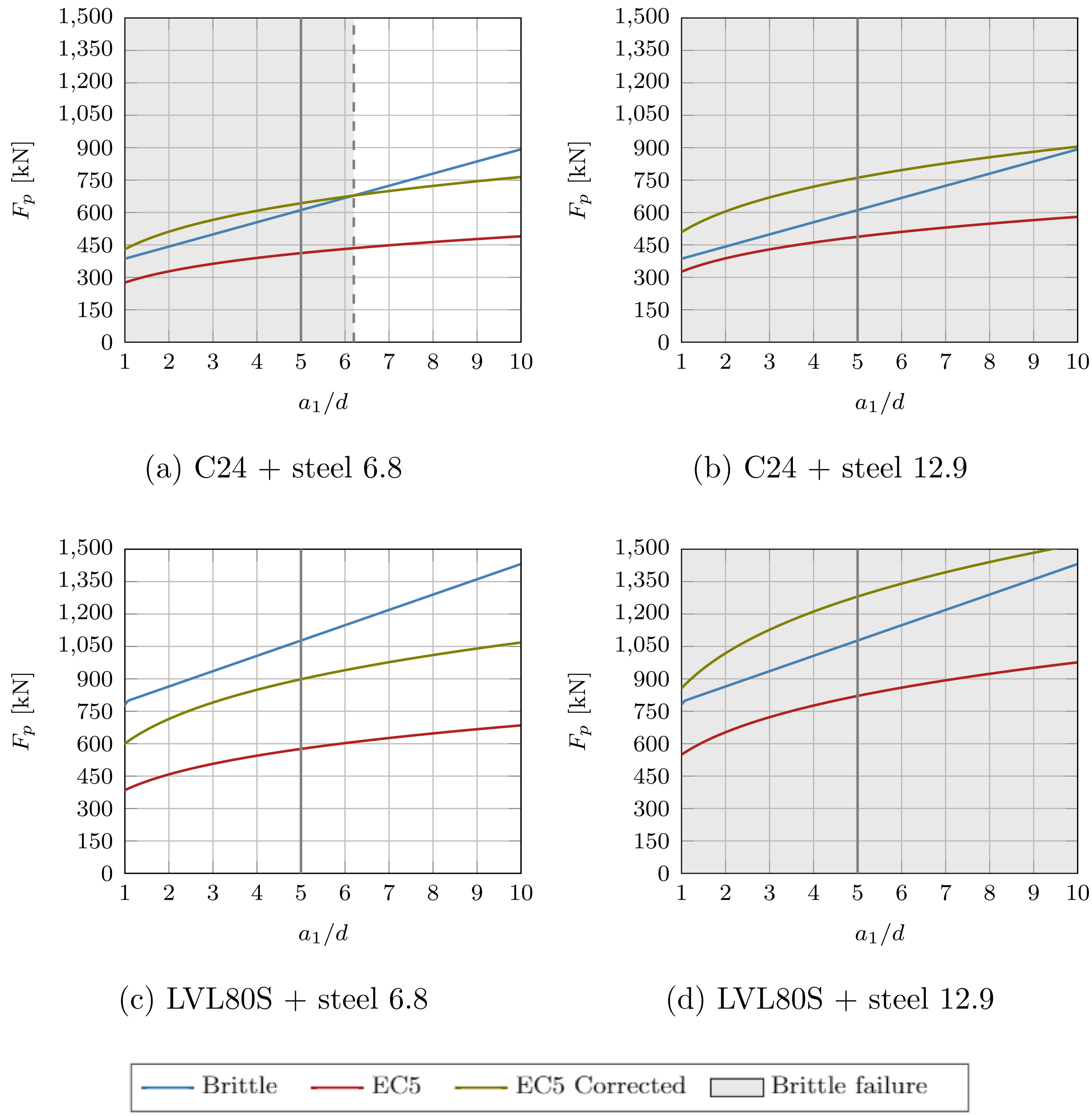



**Fig. 11.** Parametric analysis of the influence of the spacing between columns of fasteners $a_1$ on the predicted load capacity $F_p$ considering the brittle model from Yurrita and Cabrero [15], the model from Eurocode 5 [6] and its corrected version according to Section 3.

In this case, very few cases are expected to reach brittle failure mode. Almost no cases under the limitation established by Eurocode 5 [6] are found when using the steel grade 6.8 (Fig. 12c and Fig. 12a). In the case of the high grade steel 12.9, the limitation of Eurocode 5 [6] seems not enough. A distance $a_1/d = 3.6$ is required when combined with LVL80S ((Fig. 12d), which increases to $a_1/d = 4.15$ when timber C24 is used (Fig. 12b).

Analysis of the influence of distance to the loaded end edge $a_3$.

The last analysed parameter is the distance from the last column of fasteners to the end-loaded edge of the connection $a_3$ (see Fig. 13). The studied range is in between $a_3/d = 1$ and $a_3/d = 15$, considering also the limit given in Eurocode 5 [6] of $a_3/d = 7$.

Another time, problems with the correct discrimination of the failure mode are found when 12.9 steel is chosen as the timber product (Fig. 13b and Fig. 13d. In the case of C24 with 6.8 steel (Fig. 13a), a distance slightly higher than $a_3/d = 9$ is needed to achieve ductile behaviour. Finally, another time the combination of LVL80S with steel 6.8 (Fig. 13c) appears as the safest combination, with no brittle cases.

### 4.2. General parametric analysis

Once the methodology of the parametric study has been explained with the previous example, the results from the general parametric analysis, which considers a total of 1,008 connections, are presented. The analysis includes 21 different geometries of fastener distributions, from a basic connection of $2 \times 2$ ($n_r \times n_c$) to $8 \times 8$ connection. Each

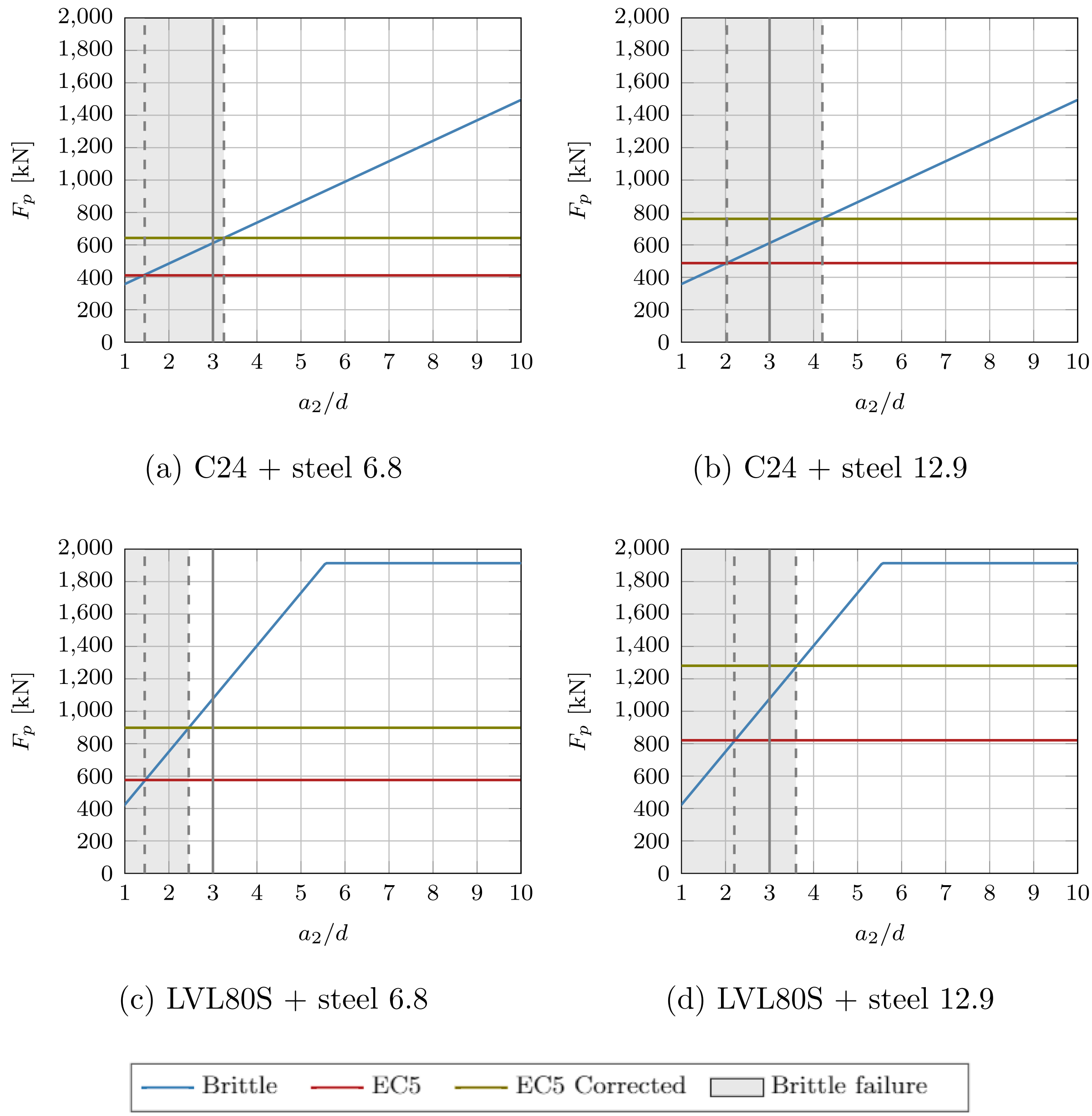



**Fig. 12.** Parametric analysis of the influence of the spacing between rows of fasteners $a_2$ on the predicted load capacity $F_p$ considering the brittle model from Yurrita and Cabrero [15], the model from Eurocode 5 [6] and its corrected version according to Section 3.

pattern has been studied for the cases of steel-wood-steel and wood-steel-wood connections, both assessed with dowels and with bolts (considering different rope effect for each fastener type, as established by Eurocode 5 [6]). Finally, three timber thickness (100, 150 and 200 mm) were considered.

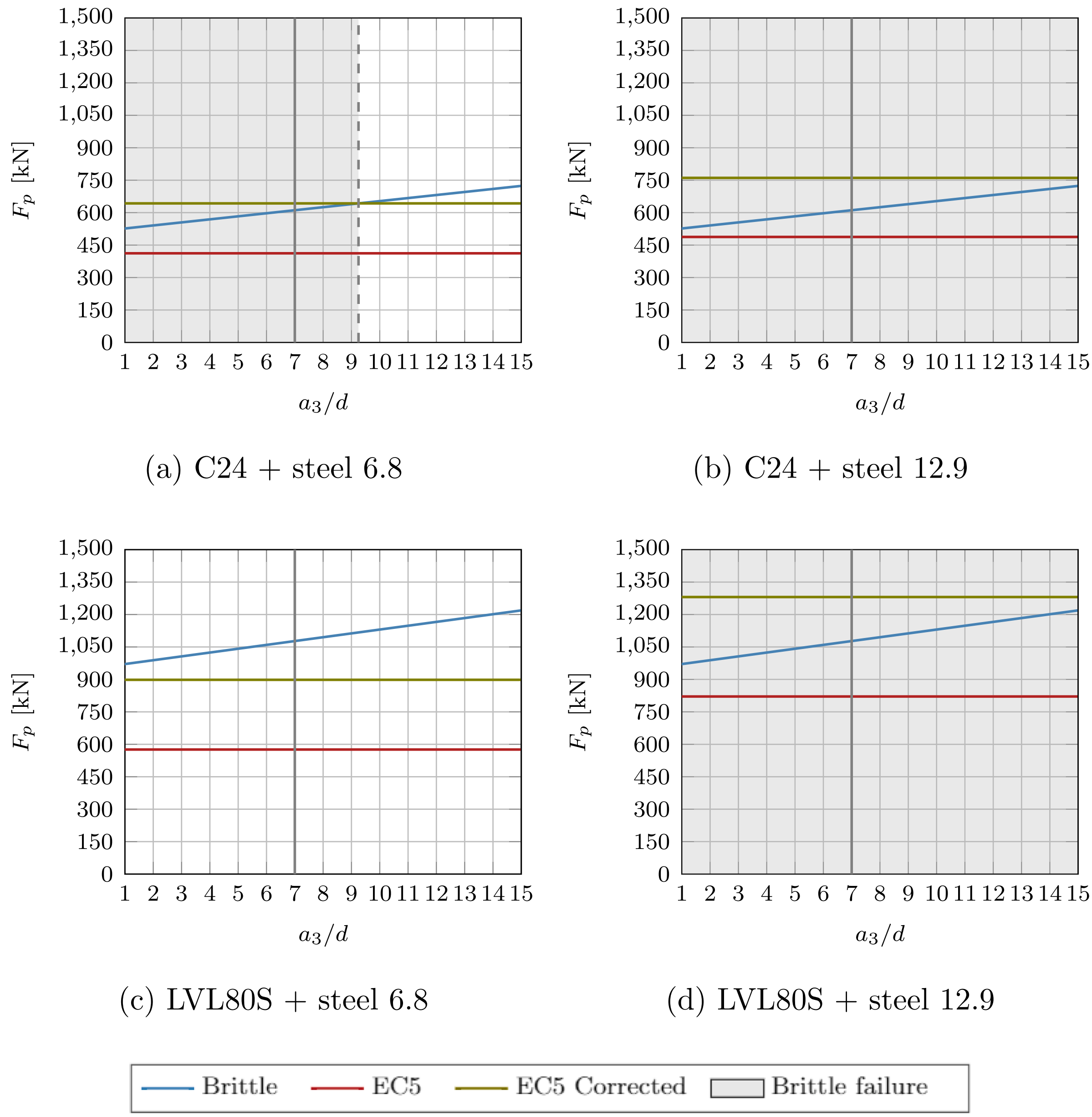
For each connection, the same process described above has been conducted, studying the four possible combinations of timber product and steel grade of fasteners, and the variation of the already explained parameters.

The following graphs (Fig. 14, Fig. 15 and Fig. 16 for timber thickness of 100, 150 and 200 mm) present the % of the studied cases in which, after comparing the approach from Eurocode 5 [6] (with the correction factor of 1.55) and the brittle model from Yurrita and Cabrero [15], a brittle failure mode is expected.

Each graph presents four cases: steel-wood-steel connections with dowels (Fig. 14a, Fig. 15a and Fig. 16a); steel-wood-steel connections with bolts (Fig. 14b, Fig. 15b and Fig. 16b); wood-steel-wood connections with dowels (Fig. 14c, Fig. 15c and Fig. 16c) and wood-steel-wood connections with bolts (Fig. 14d, Fig. 15d and Fig. 16d). In each case, four values are given, corresponding to the four material combinations (timber *C*14 with steel grades 4.8 and 10.9 and LVL80S with the same steel grades).

Several conclusions may be obtained from the parametric analysis:

- Joint configuration. The comparison between all studied cases of steel-wood-steel *sws* and wood-steel-wood *wsw* connections shows




(a) C24 + steel 6.8

(b) C24 + steel 12.9

(c) LVL80S + steel 6.8

(d) LVL80S + steel 12.9

**Fig. 13.** Parametric analysis of the influence of the distance to the end loaded edge of the timber element $a_3$ on the predicted load capacity $F_p$ considering the brittle model from Yurrita and Cabrero [15], the model from Eurocode 5 [6] and its corrected version according to Section 3.

that in all cases, the % of wrong predictions are higher in *sws* connections (17.5%) than in the *wsw* case, where the predictions are very accurate (1.9%).

- Timber thickness. The possibility of obtaining a wrong prediction of the failure mode decreases when the timber thickness (or the fastener slenderness) is increased: 14.7% for $t = 100$ mm; 7.5% for $t = 150$ mm and 4.3% for $t = 200$ mm. The rate of ductile cases relates to the yielding mode of the fastener.
- Used materials. The most risky case is clearly the combination of *C*24 timber with 12.9 steel (17.3% of wrong cases). The combination of softwood with a high steel grade makes it easier to produce a wood crack before the fastener yields. Just the opposite happens when a hardwood is combined with a low steel grade, as plastic hinges in the fasteners are more likely. Therefore, in the combination of LVL80S and 6.8 steel grade only 2.6% of brittle cases are expected.
- Influence of the number of fasteners. Those connections with a reduced number of fasteners have a lower probability of reaching a brittle failure mode (i.e., the configuration with a 2x2 mesh presents 0% of brittle cases). The rate increases when the number of fasteners is higher: connections with 8x8 fasteners have, conversely, an average rate of 38.4% of being wrongly predicted.
- Influence of the type of fastener. The rope effect considered by Eurocode 5 [6] for bolts is limited to 25% of the EYM capacity, and it is dismissed for dowels. As shown in Fig. 17, the resulting variation is

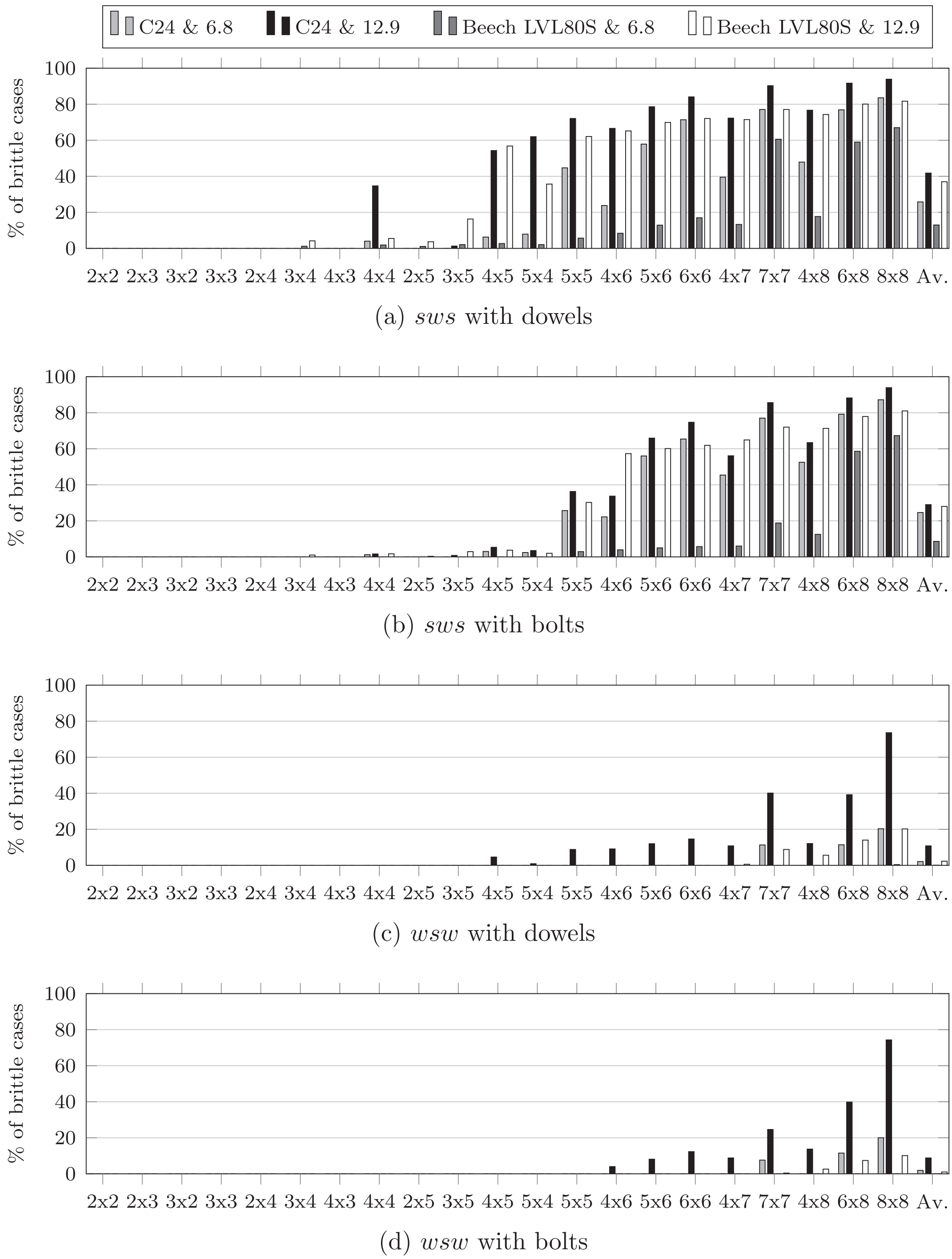



**Fig. 14.** Parametric study considering the % of brittle cases non predicted by the Eurocode 5 [6], considering a timber thickness $t = 100$ mm. Last column provides the mean value for all the analysed cases.

insignificant: 9.7% of brittle cases for dowels and 7.9% for bolts. The slightly better performance of connections with bolts relates to the increase in the ductile load-carrying capacity due to the consideration of the rope effect. It has been found that mode H (which includes rope effect, Fig. 4h) was the most common in *wsw* configurations, while in the case of *sws* configurations, the resulting yielding modes were more related to the slenderness of the fastener $t/d$.

## 5. Proposal

As shown in Section 4, the conservative trend in the load capacity prediction of Eurocode 5 [6] may lead to wrong predictions of the failure mode. The used correction factor of 1.55 has been only developed for illustrative purposes in the parametric analysis, but being dependent on the compiled database, it should not be regarded as a general proposal.

An alternative way to reduce the observed conservative trend of

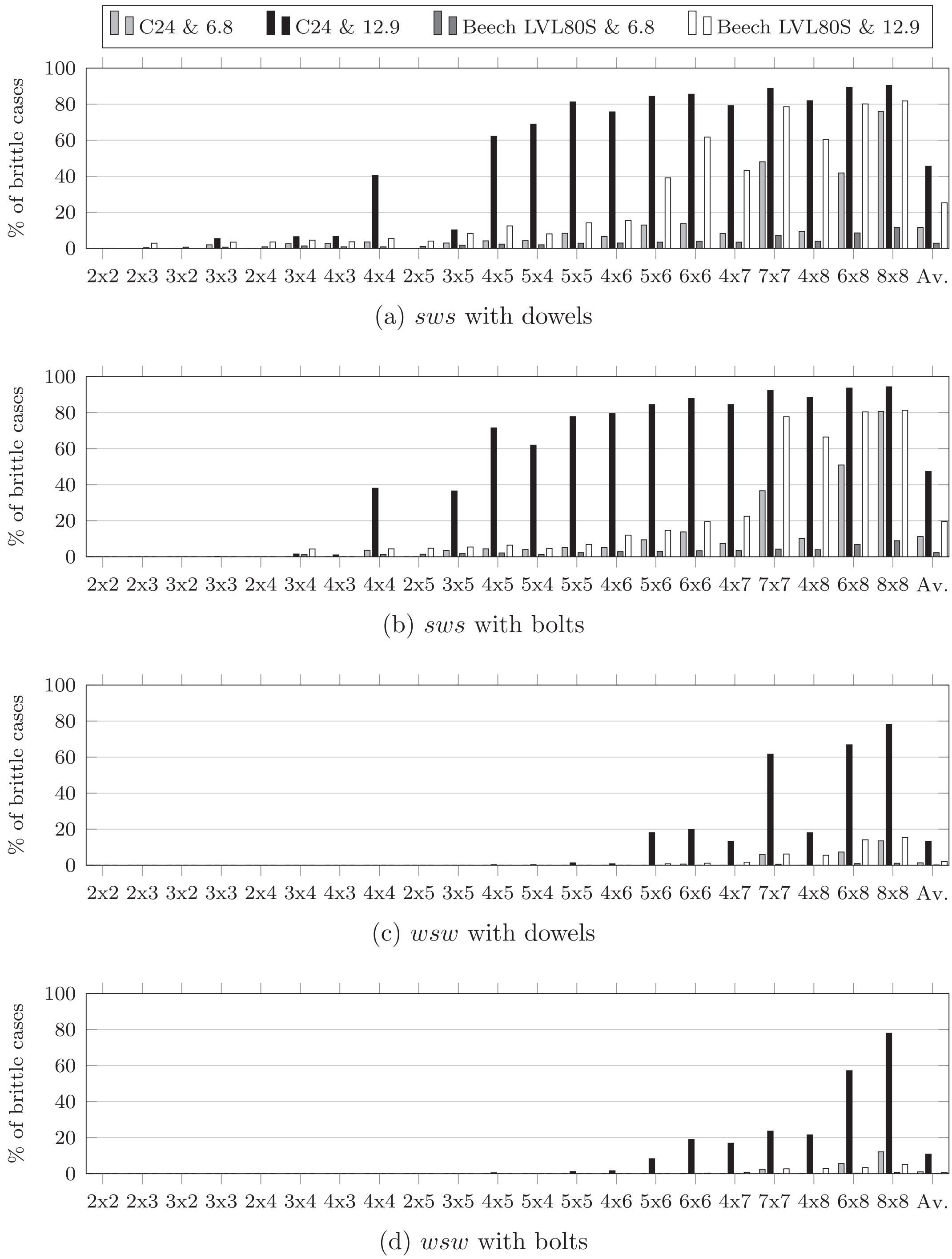



**Fig. 15.** Parametric study considering the % of brittle cases non predicted by the Eurocode 5 [6], considering a timber thickness $t = 150$ mm. Last column provides the mean value for all the analysed cases.

Eurocode 5 [6] could be not including the effective number of fasteners $n_{ef}$. This reduction parameter was introduced to reduce the predicted load-carrying capacity of the connection to include some of the brittle failure modes, but it also leads to an inaccurate prediction of the load-carrying capacity and, at the same time, it does not allow a correct prediction of the failure mode of a connection.

The EYM being a plastic model, based on the yielding of the fastener, it may be considered that when the ductile load-carrying capacity is reached, the initially uneven load distribution among fasteners has been redistributed [20].

A boxplot, similar to the one shown in Fig. 6, but in which now Eurocode 5 [6] without the $n_{ef}$ parameter is evaluated, is presented in Fig. 18. It can be seen how the prediction accuracy obtained for the considered test campaigns (excluding the one from Jorissen [11]) is

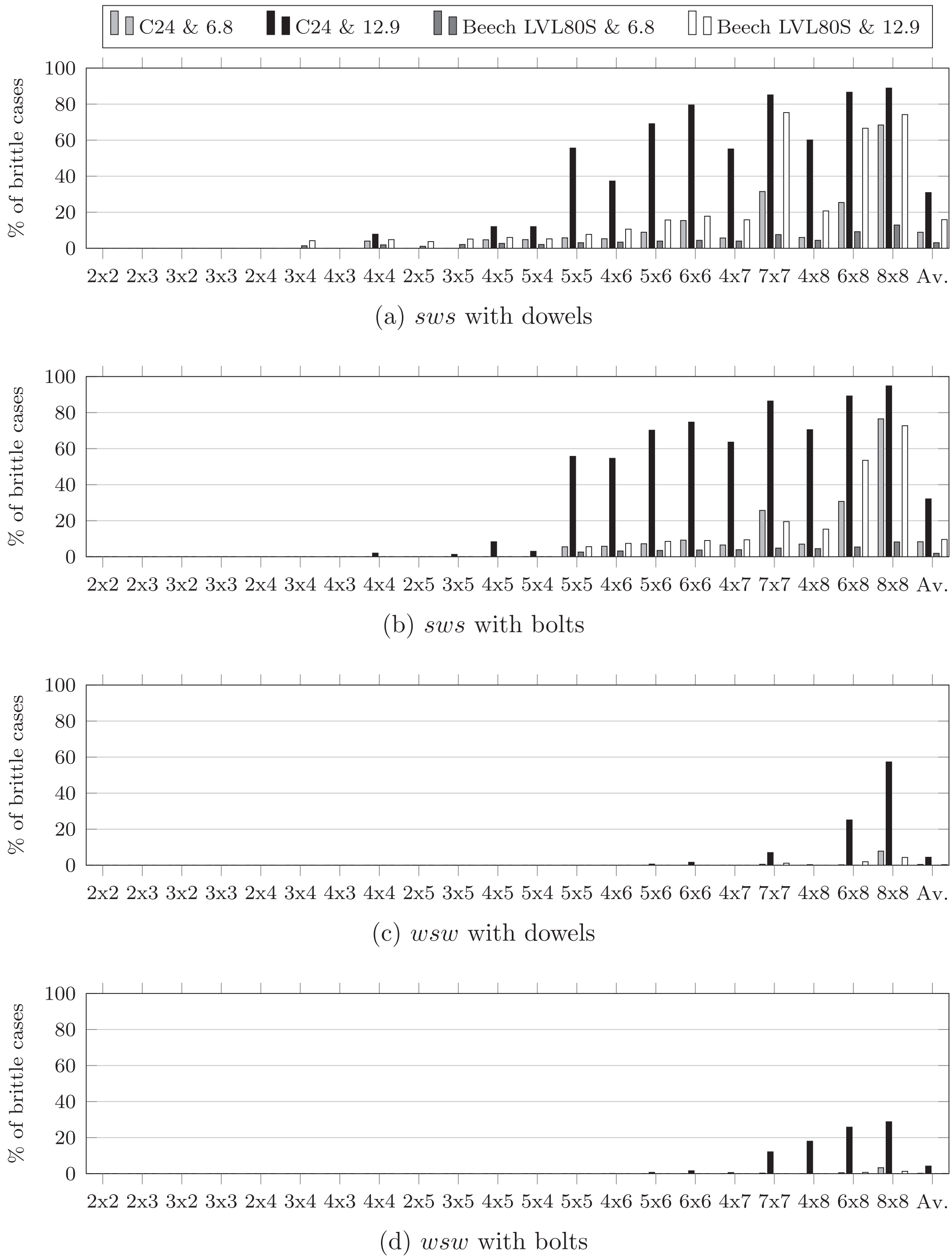



**Fig. 16.** Parametric study considering the % of brittle cases non predicted by the Eurocode 5 [6], considering a timber thickness $t = 200$ mm. Last column provides the mean value for all the analysed cases.

improved, with average and median values closer to the ideal ratio $F_p/F_t = 1$ (in between 0.74 from the tests of Ehlbeck and Werner [27] and 1.04 of Blaß and Schmid [28]).

As shown in Fig. 19, the overall prediction accuracy of Eurocode 5 [6] without including the reduction factor $n_{ef}$ improves. The slope value increases to $m = 0.838$, while the correlation coefficient $R^2$ remains almost constant to the values previously given in Fig. 7a (from 0.917 to 0.909). As a consequence, if used, the former correction factor of 1.55 (required to obtain a perfect slope $m = 1$ in Fig. 7c) is reduced to 1.13.

The study of ductile and brittle failure modes separately can lead to a more accurate prediction of the load-carrying capacity and, at the same time, the actual failure mode of the connection could be assessed. To evaluate the possible improvement, a similar parametric analysis as the one performed in Section 4 has been conducted. Now, the model includes the brittle failure approach from Yurrita and Cabrero [15] and

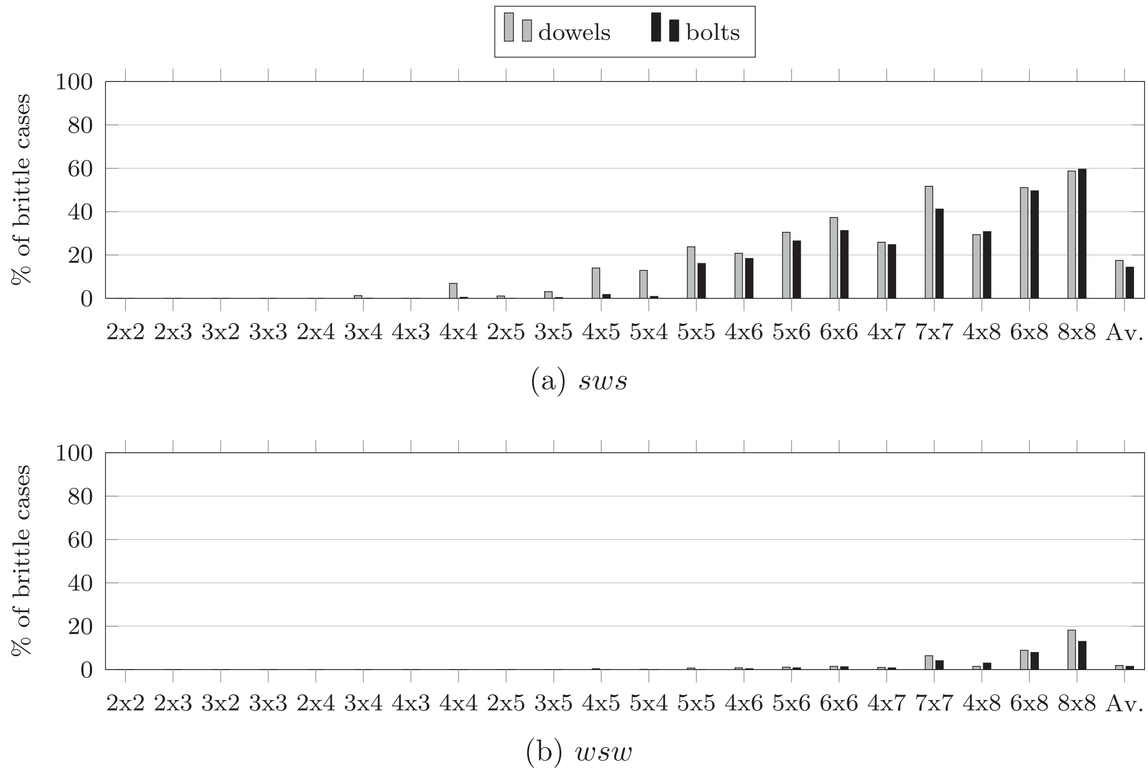



**Fig. 17.** Parametric study considering the differences on the % of brittle cases non predicted by the Eurocode 5 [6] when using dowels or bolts. Last column provides the mean value for all the analysed cases.

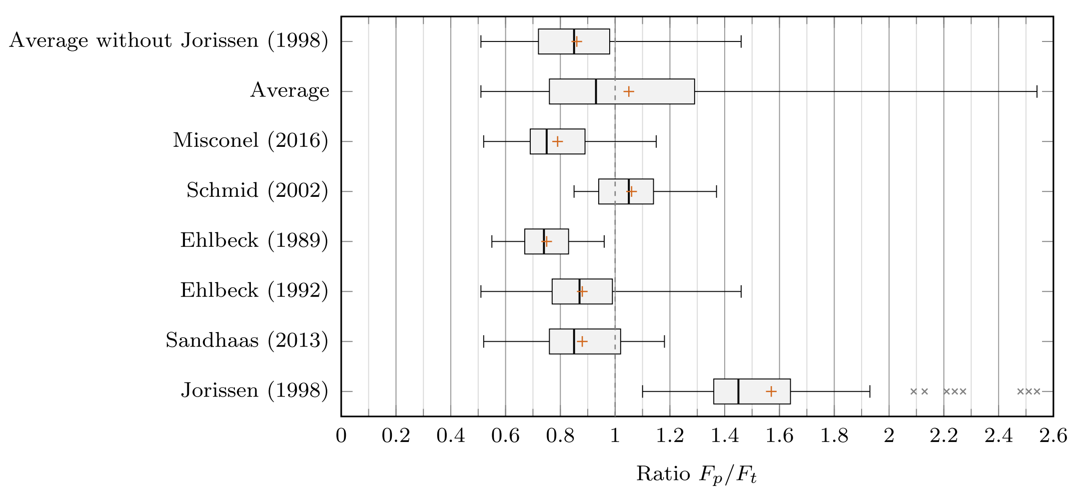



**Fig. 18.** Boxplot assessing the accuracy obtained by the Eurocode 5 [6] without the $n_{ef}$ parameter when compared with the test results from the studied authirs, considering the accuracy of the predicted ratio between the predicted failure load $F_p$ and the tested failure load $F_t$.

the ductile approach of the EYM without the $n_{ef}$ parameter, with the correction factor of 1.13. Fig. 20 compares the new obtained prediction accuracy of the new parametric analysis with the former one. Steel-wood-steel *sws* and wood-steel-wood *wsw* connections are evaluated separately. The three considered timber thickness (100, 150 and 200 mm) are plotted for each of the 21 different fastener distributions.

In the case of steel-wood-steel connections, a clear reduction of the cases reaching brittle failure mode can be noticed. In average, the original value of 17.5% (Fig. 20a) is reduced to 6.6% (Fig. 20b). In addition, the increasing tendency related to connections with higher number of fasteners is minimised, as the $n_{ef}$ penalises specially those cases.

Regarding wood-steel-wood connections, the average behaviour remains almost similar. Eurocode 5 [6] (Fig. 20c) obtains 1.9%, while the proposal (Fig. 20d) slightly increases the value to 2.2%. However, the same tendency of increasing the risk of reaching a brittle failure

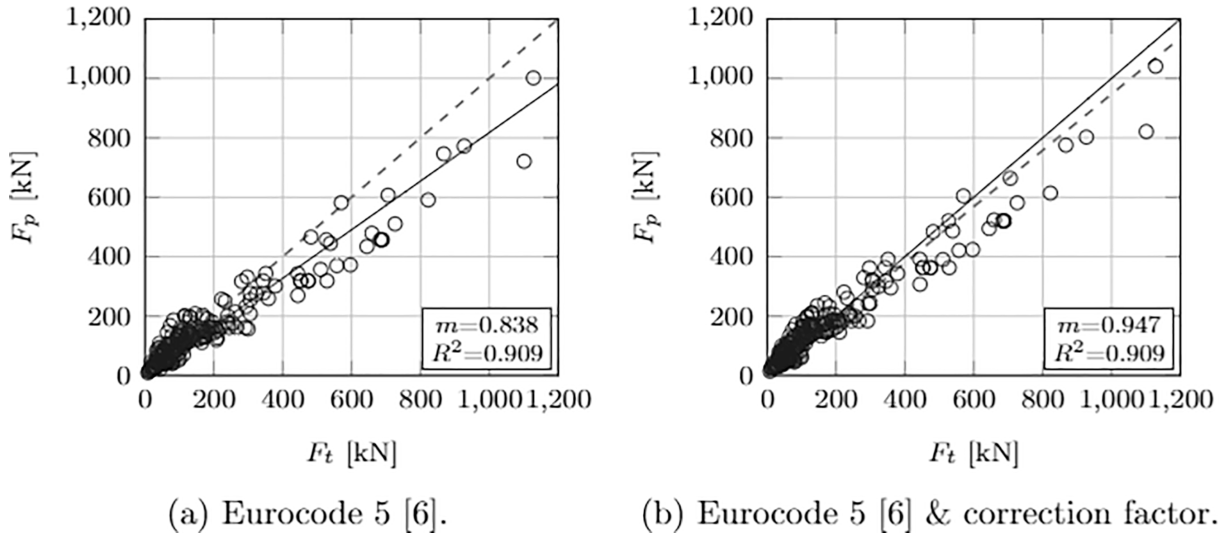



**Fig. 19.** Comparison between the load capacity values obtained from the tests $F_t$ and the corresponding theoretical values $F_p$ predicted by the ductile approach from the Eurocode 5 [6] without the $n_{ef}$ parameter before and after applying a correction factor of 1.13.

mode on connections with more fasteners is noticed.

As a summary, Table 2 compares the results of the analysis, showing the % of brittle cases expected when applying both models (EYM combined with the $n_{ef}$ and the proposal that dismiss this reduction factor). The table includes all cases considered in the already conducted parametric analysis. Moreover, the difference of % between both models and the ratio of improvement are provided. The table divides the analysis regarding several classifications (type of connection, timber thickness, material combination, and type of fastener). It can be seen how the reached improvement is higher in the cases where brittle failure mode is more likely to happen such as with lower thicknesses or the combination of softwood with high steel grade. In total, a reduction of 53.6% of the brittle cases is achieved.

### 5.1. Comparison of the discrimination ability

Finally, an analysis comparing the discrimination ability to determine the failure mode (ductile or brittle) between the model from Eurocode 5 [6] and the proposal has been conducted. Since the combination of the EYM and the $n_{ef}$ from Eurocode 5 [6] does not allow to strictly determine the failure mode, this analysis has been performed under the hypothesis that this model predicts a ductile failure mode.

For the analysis, the brittle database ([21,22,24,31,38–49]) used by Yurrita and Cabrero [15] to validate the brittle model has been used together with the ductile database ([11,26–31]) described in this work (Table 1). This database includes a total of 420 configurations, 61.0% brittle and 39.0% ductile. The load capacity of each test configuration predicted by Eurocode 5 [6] original model and the proposal without the $n_{ef}$ parameter were compared with the brittle predictions from Yurrita and Cabrero [15]. The expected failure mode (ductile or brittle), corresponds to the lower capacity, which it is compared with the experimentally observed failure mode.

Fig. 21 depicts the result of this analysis. The dark filled parts correspond to the correct predictions (true ductile and true brittle), while the clear filled parts show the % of wrong predictions (false ductile and false brittle).

It is clear how the original model from Eurocode 5 [6], due to its conservative trend, leads usually to a ductile failure mode prediction. 70.7% of the cases are expected to reach a ductile failure mode, while only 39% of the configurations failed under this failure mode. A total of 33.3% false ductile cases are predicted.

In contrast, the proposal reduces the number of ductile predictions to 38.1%, with only 4.5% of false ductile predictions. Furthermore a good prediction of brittle cases (56.4% of true brittle and only 5.5% of false brittle) is achieved.

In total, the original model from Eurocode 5 [6] (with $n_{ef}$) gets 65.0% of positive matches. The proposal clearly improves this trend with a total of 90.0% of correct predictions.

## 6. Conclusions

The ductile model included on Eurocode 5 [6] has been demonstrated to be consistent but, at the same time, conservative. Based on the results of analysis of the database of experimental tests, an illustrative correction factor of 1.55 would lead, in average, to a more accurate model.

A parametric study comparing both the ductile model of Eurocode 5 [6] and the corrected one with the brittle model proposed by Yurrita and Cabrero [15] has been performed. This study demonstrates that in many cases a brittle failure mode may be achieved when ductile failure mode is expected. This can lead to risky situations, specially in seismic areas or structures subjected to other accidental loads. Therefore, when looking at the resulting failure mode, the conservative trend of Eurocode 5 [6], instead of being on the side of safety, may be unsafe, due to the wrong estimation of the failure mode.

To improve the model from Eurocode 5 [6], a proposal in which ductile (the model from Eurocode 5 [6] but without the $n_{ef}$ parameter), and brittle (according to Yurrita and Cabrero [15]) failure modes are considered separately, is presented. The analysis demonstrates how this combination of dedicated models allows to achieve more accurate predictions of the ductile load-carrying capacity and it also improves the capacity to correctly identify the expected failure mode of the studied connection.

The resulting improvement is confirmed by means of an extensive database of brittle and ductile tests, which has been used to evaluate the discrimination ability between the failure modes of the original

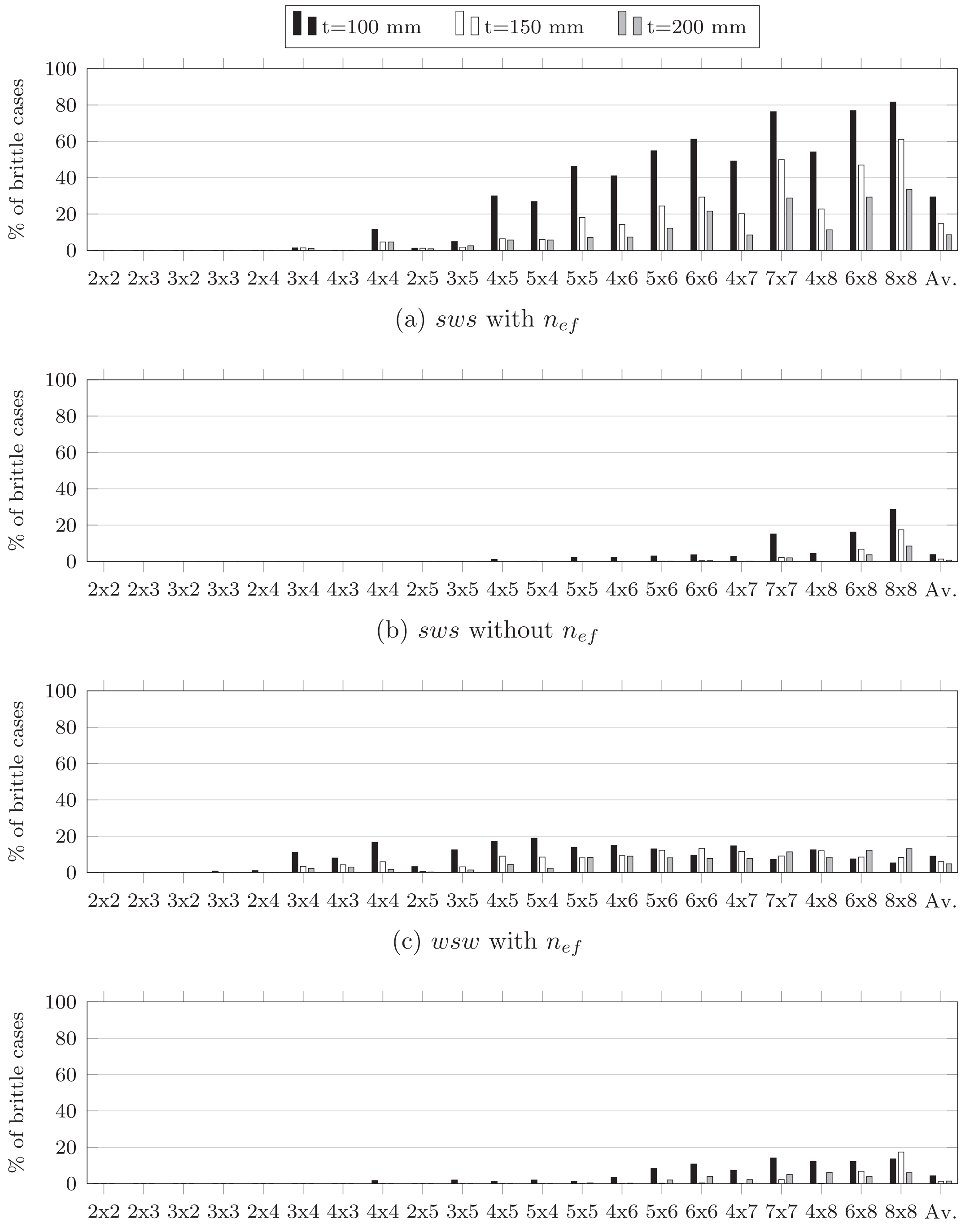



**Fig. 20.** Parametric study considering the % of brittle cases non predicted by the Eurocode 5 [6] (including $n_{ef}$) and the proposal (without $n_{ef}$). Last column provides the mean value for all the analysed cases.

**Table 2**
Summary of the % of wrong predicted cases. Comparison between the Eurocode 5 [6] (with $n_{ef}$) and the proposal (without $n_{ef}$). All values are given in %.

| | Configuration | | Thickness $t$ [mm] | | | Material combination | | | | Fastener | | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *sws* | *wsw* | 100 | 150 | 200 | C24 & 6.8 | C24 & 12.9 | LVL & 6.8 | LVL & 12.9 | Dowel | Bolt | Total |
| Eurocode 5 [6] | 17.5 | 1.9 | 14.7 | 7.5 | 4.3 | 6.8 | 17.3 | 2.6 | 8.7 | 9.7 | 7.9 | 9.7 |
| Proposal | 6.6 | 2.2 | 7.8 | 5.1 | 3.9 | 4.2 | 7.3 | 1.9 | 4.6 | 4.5 | 4.5 | 4.5 |
| Difference | 10.9 | −0.3 | 6.9 | 2.4 | 0.4 | 2.6 | 10 | 0.7 | 4.1 | 5.2 | 3.4 | 5.2 |
| Improvement | 62.3 | −15.8 | 46.9 | 32 | 9.3 | 38.2 | 57.8 | 26.9 | 47.1 | 53.6 | 43 | 53.6 |

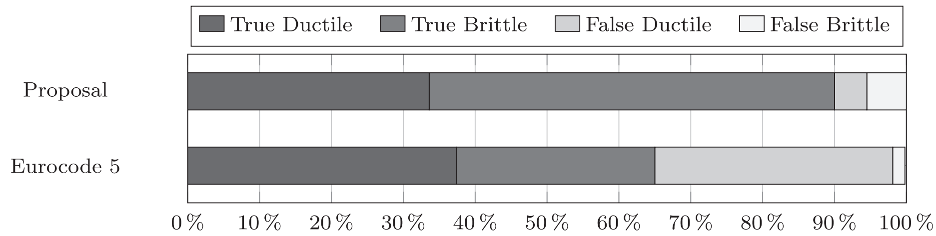



**Fig. 21.** Discrimination ability. Comparison between Eurocode 5 [6] (assuming that the EYM predicts a ductile failure), and the proposal.

model and the proposal. This analysis determines that Eurocode 5 [6] reaches a total of 65.0% of correct predictions, wile the proposal increases the percentage of positive matches to 90.0%.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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